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RESEARCH ARTICLE

Spatial-temporal variations of natural suitability of human settlement environment in the Three Gorges Reservoir Area—A case study in Fengjie County, China

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Abstract With rapid environmental degeneration and socio-economic development, the human settlement environment (HSE) has experienced dramatic changes and attracted attention from different communities. Consequently, the spatial-temporal evaluation of natural suitability of the human settlement environment (NSHSE) has become essential for understanding the patterns and dynamics of HSE, and for coordinating sustainable development among regional populations, resources, and environments. This study aims to explore the spatial-temporal evolution of NSHSE patterns in 1997, 2005, and 2009 in Fengjie County near the Three Gorges Reservoir Area (TGRA). A spatially weighted NSHSE model was established by integrating multi-source data (e.g., census data, meteorological data, remote sensing images, DEM data, and GIS data) into one framework, where the Ordinary Least Squares (OLS) linear regression model was applied to calculate the weights of indices in the NSHSE model. Results show that the trend of natural suitability has been first downward and then upward, which is evidenced by the disparity of NSHSE existing in the south, north, and central areas of Fengjie County. Results also reveal clustered NSHSE patterns for all 30 townships. Meanwhile, NSHSE has significant influence on population distribution, and 71.49% of the total population is living in moderate and high suitable districts.

Keywords natural suitability of human settlement environment, ordinary least squares model, global and local spatial autocorrelation analyses, Three Gorges Reservoir Area (TGRA), Fengjie County

1 Introduction

According to the well-known report "Our Common Future" published in 1987 by the UN World Commission on Environment and Development (the Brundtland Commission), the human settlement environment (HSE) is viewed as one of the key factors in sustainable development (Burton, 1987). HSE, which refers to the totality of the human community (e.g., city, town, or village), is an important combination of the natural, human, spiritual, political, cultural, and economic environments. It is also associated with broader systems at the regional and global levels for resource input and waste output (Hassan et al., 2005). Since the concept of "Science of Habitat Environment" was proposed in the 1960s (Doxiadĺes, 1977), many studies in the fields of architecture and urban planning (Ruda, 1998; Pugh, 2000), geography (Rojas, 1989), ecology (Silbernagel et al., 1997), etc. (Zebardast, 2009), have been carried out on this topic.

With the development of Remote Sensing (RS) and Geographic Information System (GIS) techniques, many HSE studies have been able to cover a number of subtopics, including settlement evolution (Giraud, 2009; Zhou et al., 2013), settlement patterns modeling (Schnaiberg et al., 2002; Ford et al., 2009), informal settlements (Zeilhofer and Topanotti, 2008; Dubovyk et al., 2011; Owen and Wong, 2013), HSE evaluation (Zhao et al., 2002; Li and Dovers, 2011; Xu et al., 2012; Ouzounis

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et al., 2013; Wei et al., 2013; Charoenkit and Kumar, 2014), and socioeconomic roles and sustainable management (Huang et al., 1998; Shen et al., 2013). Generally, HSE evaluation studies have followed several trends. First, the research contents have been widely extended from focusing on the perspective of cultural environment factors (e.g., public safety, social economic, education conditions, and transportation) to now including natural factors (e.g., topography, climate) (Van Kamp et al., 2003; Godard, 2013; Shen et al., 2013; Marans, 2015). Therefore, it is of great importance to explore the natural properties of HSE for the sake of sustainable HSE development. Although current research of natural factors mainly focuses on a single factor, such as climate (Emmanuel, 2005; Jenerette et al., 2007; Krüger et al., 2013; Luo et al., 2017), topography (Horikoshi and Kagami, 1991), and land cover (Zhang et al., 2011; Tian et al., 2012), it should be extended to multi-factor analysis. Second, the adopted data include both statistical data and geographic information (e.g., satellite imagery, GIS data, etc.) (Tian et al., 2012; Xu et al., 2012; Ouzounis et al., 2013; Wei et al., 2013). Third, compared with traditional ecological and geographical methods, the recently proposed methods have been significantly improved by using mathematical tools and pattern recognition methods like hierarchy analysis (HA), analytic hierarchy process (AHP), fuzzy evaluation (FE), genetic algorithm (GA), and statistical learning (SL), etc. (Xu et al., 2012; Ouzounis et al., 2013; Shen et al., 2013; Xu and Li, 2014). In conclusion, the studies in HSE have developed rapidly in terms of scope and methods. However, there are still some limitations to exploring the evolution of natural factors, especially for multi-temporal evaluation of different factors. Furthermore, it is urgent to conduct integrated and dynamic research at the county and town scales based on multi-source data and the spatial analysis method.

The Three Gorges Reservoir Area (TGRA) is an important zone along the Yangtze River and will be increasingly significant for the progress of China. Taking Fengjie County (the center area of the TGRA) as a case study area, the specific objectives of this work are: 1) to establish an integrated model to quantitatively and dynamically evaluate the spatial-temporal dynamics of NSHSE in 1997, 2005, and 2009 by using multi-source data (meteorological site data, census data, remote sensing images, DEM data, and GIS data); 2) to analyze the spatial-temporal patterns of NSHSE of Fengjie County for the stated periods with global and local spatial autocorrelation analyses; and 3) to explore the rationality of population distribution based on the NSHSE and to provide decision support for the immigrants of the Three Gorges Project.

2 Study area

Considering its own typicality and the importance of a natural environment, Fengjie County is taken as a case area to represent NSHSE in the TGRA. Fengjie County, the central area of the TGRA, lies in the upper reaches of the Yangtze River and northeast of Chongqing city, southwest China (109°1′17″–109°45′58″E, 30°29′19″–31°22′33″N). It administers 30 townships (Fig. 1), covers 4087 km^2 and had a total population of 1.06 million at the end of 2015 (Chongqing Municipal Bureau of Statistics and National Bureau of Statistics Survey Office in Chongqing, 2016). Two main mountains, the Qiyao and Wushan Mountains, whose altitudes are both above 1800 m, are situated in the southern part of Fengjie County. Fengjie County has a humid subtropical monsoon climate with a mean annual temperature of 17.8°C (extreme maximum temperature: 39.8°C and extreme minimum temperature: –9.2°C), annual average frost-free period of 287 days, average annual precipitation of 1132 mm, relative humidity of 65%, and annual sunshine duration of 1639 hours. The main types of soil are paddy, alluvial, purple, yellow, yellow brown, brown, lime, etc. The water resources are rich since this area includes the Yangtze River (which flows through the entire middle of the county), the Meixi River, and the Daxi River. The zonal natural vegetation comprises the subtropical evergreen broadleaf forest and the warm coniferous forest.

3 Materials and methods

The overall flowchart of the proposed method is shown in Fig. 2, which includes the following steps:

Step 1: data preprocessing to include atmospheric correction by using FLAASH, geocoding, re-projecting coordinate system, etc. and to construct a geodatabase for the purpose of integrating multiple data sets.

Step 2: establishing an index system.

Step 3: analyzing the spatial-temporal patterns of NSHSE and the rationality of population distribution in Fengjie County.

3.1 Data and preprocessing

In this study, topography, climate, water resource conditions, and land cover are considered as the fundamental factors expected to contribute to NSHSE. As shown in Fig. 2 and Table 1, two categories of data are used in this study: 1) statistical/tabular data, including census data and meteorological data (i.e., monthly average temperature, precipitation, wind speed, sunshine time, and relative humidity); and 2) spatial data, including satellite images (Landsat TM images), topographic data (DEM), and vector data (land cover data and administrative division map).

DEM and vector data were assumed consistent, and all other data were captured in 1997, 2005, and 2009. Landsat TM images of the same season with less than 10% cloud cover (the path-126/ row-38 and row-39) are used, and

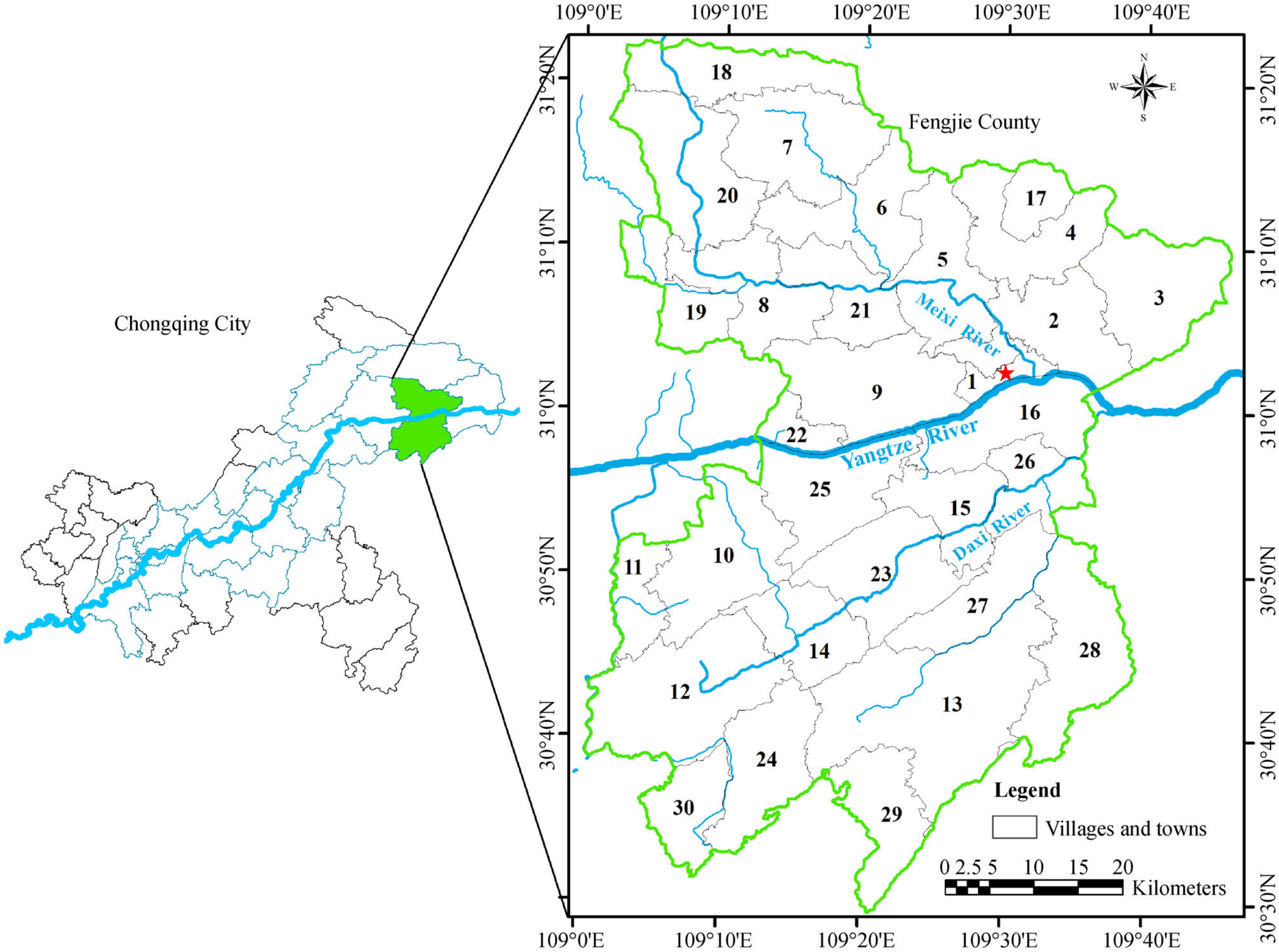

Fig. 1 Study area: Fengjie County (Chongqing City, China) with 30 townships. 1- Yong'an, 2- Baidi, 3- Caotang, 4- Fenhe, 5- Kangle, 6- Dashu, 7- Zhuyuan, 8- Gongping, 9- Zhuyi, 10- Jiagao, 11- Yangshi, 12- Tuxiang, 13- Xinglong, 14- Qinglong, 15- Xinmin, 16- Yongle, 17- Yanwan, 18- Ping'an, 19- Hongtu, 20- Qinglian, 21- Shigang, 22- Kangping, 23- Wuma, 24- Taihe Tujiazu, 25- Anping, 26- Hefeng, 27- Fengping, 28- Chang'an Tujiazu, 29- Longqiao Tujiazu, 30- Yunwu Tujiazu.

DEM data were downloaded from USGS Earth Resources Observation and Science (EROS) Center. Meteorological data were collected from 35 meteorological sites and provided by the Chongqing Municipal Bureau of Meteorology. Census data (i.e., population data) were obtained from Fengjie County Bureau of Statistics. Land cover data and administrative division maps were collected from the Geomatics Center of Chongqing. It should be noted that, in this research, land covers are generally classified as having six categories (cropland, woodland, grassland, water, construction land, and unused land) and nineteen subclasses.

By considering the impact of terrain factors on climate elements and the distribution of meteorological sites, the maps of the monthly average temperature, sunlight, wind, rainfall, and humidity were generated using a thin plate spline interpolation method that is supported by special climatic data spatial interpolation software ANUSPLIN 4.4 (Hutchinson and Xu, 2013). Additionally, a normalized difference vegetation index (NDVI) was computed from Landsat images, which were pre-processed through terrain correction and FLAASH atmospheric correction. All grid-based data were resampled to 30 m resolution and were converted to the Gauss Kruger projection (Xian_1980_3_-Degree_GK_Zone_37).

3.2 Index system

An integrated NSHSE model with four broad categories of indices (topography, climate, hydrology, and land cover) (Step 2 of Fig. 2) demonstrates sixteen NSHSE indices were established in a hierarchical system, including Level 1 indices (Altitude, Relative Height, Slope, Temperature, Wind Speed, Sunshine Time, Humidity, Precipitation, Water Area Ratio, NDVI, and Land Use Type), Level 2 indices (Relief Amplitude Index (Feng et al., 2009), Human Thermal Comfort (including Temperature Humidity Index (Thom, 1959) and Wind Effect Index (Siple and

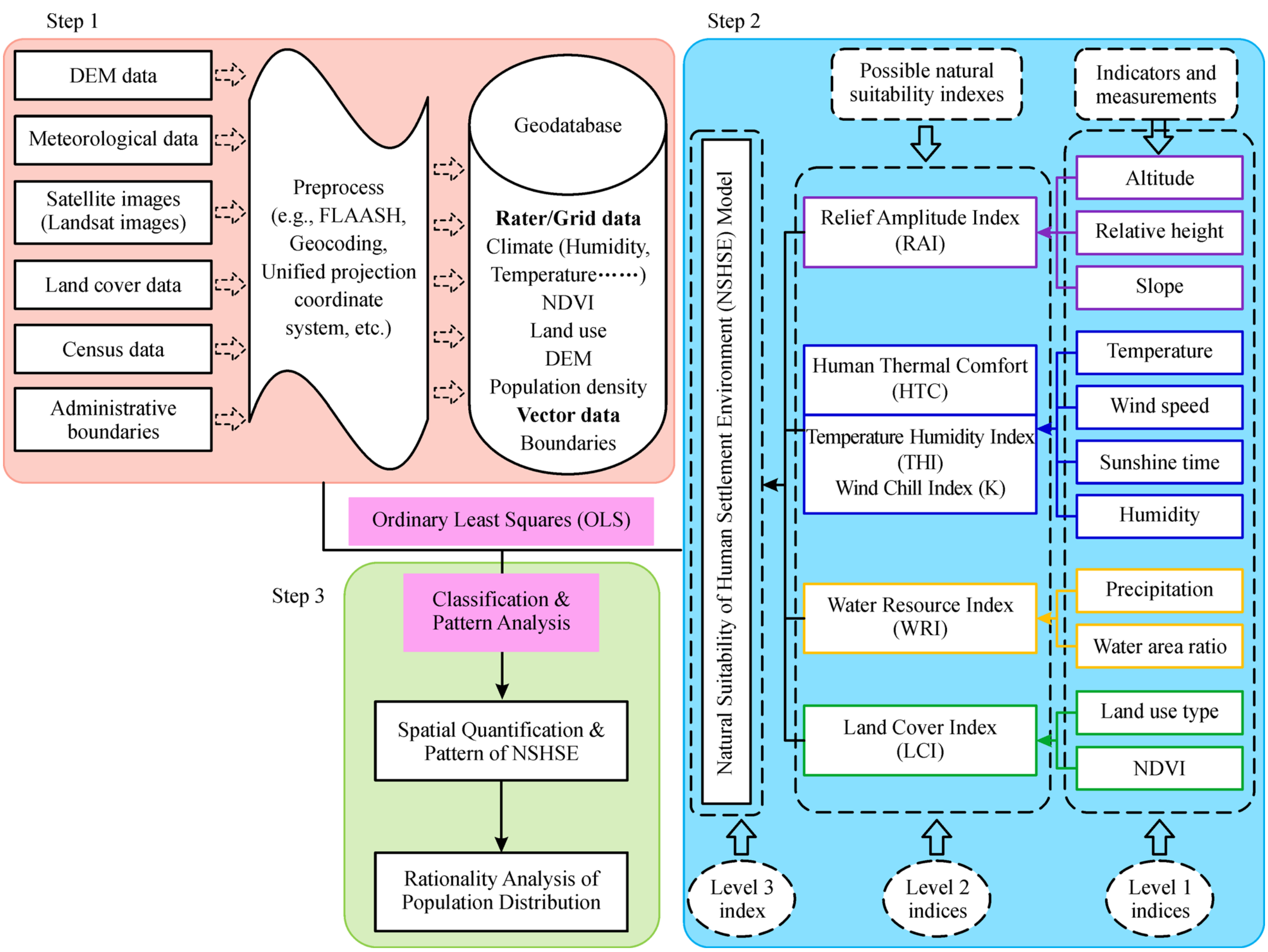

Fig. 2 The overall flowchart of the proposed method.

Passel, 1945)), Water Resource Index (Feng et al., 2009), and Land Cover Index (SEPAC, 2006)), and a Level 3 index (the overall Natural Suitability of Human Settlement Environment Index).

3.2.1 Relief Amplitude Index (RAI)

The relief amplitude is an important indicator that can be used to reflect regional terrain and can be characterized by the altitude and steep degree of a region. The calculation formula of the relief amplitude index is (Feng et al., 2009):

$$\mathrm{RAI} = AE/1000 + \{[\max(H) - \min(H)] \times [1 - P(A)/A]\}/500, \tag{1}$$

where AE is the regional average elevation in a certain window area, $\max(H)$ and $\min(H)$ represent the highest and lowest elevation respectively, and $P(A)$ and A are the flat and total area of the region. Based on change point analysis, the window size of 21×21 is recognized as the best computational unit, and A equals 0.4 km^2.

3.2.2 Human Thermal Comfort (HTC)

Different climate elements and their various combinations produce different physiological effects on the human body. The greatest influential indicators are temperature, wind, sunlight, and humidity as these directly control heat and moisture exchange between the human body and its residential environment. Human thermal comfort (He et al., 2010) can be expressed by many biometeorological indices, such as the temperature-humidity index (THI) (Thom, 1959), the wind chill index (K) (Siple and Passel, 1945), and the physiological equivalent temperature (PET) (Höppe, 1999). In this study, THI and K were used to express human thermal sensation. THI is calculated as a combination of air temperature and humidity, and K describes the loss of energy per units of time and body surface that a human can tolerate while taking wind speed and sunshine time into account (Thom, 1959):

$$\mathrm{THI} = 58 + (1.8t - 26)(0.45 + 0.0055\mathrm{RH}), \tag{2}$$

$$K = -(10v^{0.5} + 10.45 - v)(33 - t) + 8.55s, \tag{3}$$

$$\mathrm{HTC} = \sum_{i=1}^{12} (\mathrm{RTHI}_i \times \mathrm{RK}_i), \tag{4}$$

where t is the ambient air temperature (°C), RH is the ambient relative air humidity (%), v and s respectively represent the wind speed ($\mathrm{m \cdot s^{-1}}$) and the average sunshine time of everyday (h), based on the regional characteristics and criterion of reclassification (Matzarakis et al., 1999; Tseliou et al., 2010). As shown in Fig. 3, RTHI_i and RK_i are every month reclassification values of THI and K with i representing the months.

3.2.3 Water Resource Index (WRI)

Climate change has altered temperature and rainfall patterns worldwide (Miranda et al., 2011) and therefore has increased water resource stresses (Arnell et al., 2011). According to the characteristics of the hydrological environment in the study area and the feasibility of quantitative analysis and data availability, we used the water resource index (WRI) to represent the abundance or deficiency of water resources. The precipitation embodies the capacity of water supply in a natural state, and the water area represents the catchment capacity in a region. Thus, the ratio of water area and precipitation were used to represent the abundance and deficiency of water resources (Feng et al., 2009). The formula is:

$$\mathrm{WRI} = \alpha P + \beta W_a, \tag{5}$$

where P and W_a represent the normalized precipitation and water area ratio, respectively. According to the correlation between precipitation and water area ratio and population data, the value of α and β respectively were 0.3 and 0.7.

3.2.4 Land Cover Index (LCI)

Land cover directly reflects the suitability of HSE. NDVI is considered to be an effective indicator for monitoring regional and global vegetation and ecological changes. In addition, land use changes such as agricultural expansion, deforestation, and urbanization are important consequences of human activities (Trincsi et al., 2014). These changes often influence weather patterns, land degradation, food security, disease prevalence, and water quality (Foley et al., 2005). According to the Environment Protection Industry Criterion of China (SEPAC, 2006), land cover suitability is characterized by NDVI and the weight of various land cover types (Feng et al., 2009):

$$\mathrm{LCI} = \mathrm{LT}_i \times \mathrm{NDVI}, \tag{6}$$

where LT_i is the weight of various land use types (Table 2), i represents the land use types, and NDVI is the normalized difference vegetation index.

3.2.5 The establishment of NSHSE model- a comprehensive NSHSE index

Due to the fact that each single index was originally acquired in different units of measurements, normalization was necessary based on Eqs. (7) and (8) before the indices could be used in the comprehensive model—NSHSE. Then, the Ordinary Least Squares (OLS) linear regression was performed to calculate the correlation coefficients between the four explanatory variables (RAI, HTC, WRI, and LCI) and population density. Meanwhile, the Variance Inflation Factor (VIF) values of four independent variables were also calculated to detect any collinearity problems

Table 1 Basic information of the six datasets used in this study

Data	Sources	Year	Resolution or scale
Meteorological data	Chongqing Municipal Bureau of Meteorology	1997, 2005, 2009	30 m
DEM data	USGS Earth Resources Observation and Science (EROS) Center	2003	30 m
Landsat TM images	USGS Earth Resources Observation and Science (EROS) Center	1997, 2005, 2009	30 m
Land cover data	Geomatics Center of Chongqing	1997, 2005, 2009	1:10,000
Administrative division map	Geomatics Center of Chongqing	2009	1:10,000
Census data	Fengjie County Bureau of Statistics	1997, 2005, 2009	

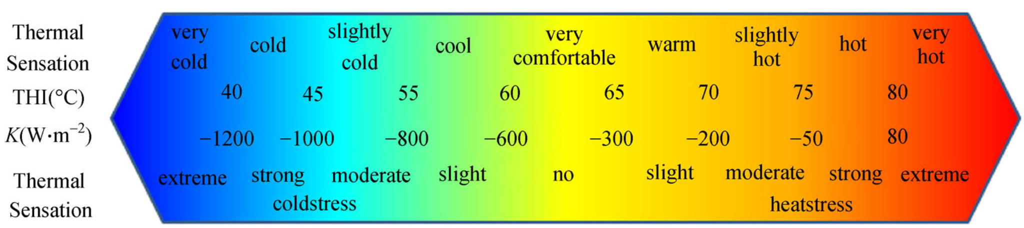

Fig. 3 THI and K range for various thermal sensation and stress levels.

Table 2 The weight of various land cover types

Land use type	Cropland		Woodland				Water			
	Paddy field	Dry land	Forest	Shrubbery	Scattered woodland	Others	River and canal	Lake	Beach	Reservoir and pond
Weight	0.08	0.07	0.1	0.08	0.06	0.06	0.05	0.05	0.03	0.04
Land use type	Grassland			Construction land			Unused land			
	High coverage	Medium coverage	Low coverage	Urban land	Rural settlement	Others	Bare land	Stone land	Others	
Weight	0.06	0.05	0.04	0.08	0.06	0.04	0.02	0.01	0.02	

among the indicators. The results indicated that the VIF values of RAI, HTC, WRI, and LCI are all less than 7.5, indicating that there are no collinearity problems among the four factors. After that, the weight of each suitability index was calculated (Table 3). Finally, the NSHSE model could be calculated as Eq. (10).

Table 3 Correlation coefficient and weight between each index and population data

Evaluation index	Correlation coefficient (c_i, i = 1,2,3,4)	Weight (w_i, i = 1,2,3,4)
RAI	0.48933	0.33577
HTC	0.17144	0.11764
WRI	0.20800	0.14273
LCI	0.58856	0.40386

$$\text{Standardized positive index value} = (\text{Index} - \text{Minimum})/(\text{Maximum} - \text{Minimum}), \quad (7)$$

$$\text{Standardized contrary index value} = 1 - (\text{Index} - \text{Minimum})/(\text{Maximum} - \text{Minimum}), \quad (8)$$

$$w_i = c_i/\sum_{i=1}^{4} c_i,\ i = 1,2,3,4, \quad (9)$$

$$\text{NSHSE} = w_1\text{NRAI} + w_2\text{NHTC} + w_3\text{NWRI} + w_4\text{NLCI}, \quad (10)$$

where c_i and w_i (i = 1,2,3,4) are respectively the correlation coefficient and the weight of the relief amplitude index, human thermal comfort, water resource index, and land cover index. NRAI, NHTC, NWRI, and NLCI correspond to the normalized relief amplitude index, human thermal comfort, water resource index, and land cover index, respectively.

3.3 Spatial classification and pattern analysis

In order to make the analysis straightforward, conventional statistical analyses were applied to objectively analyze the spatial-temporal quantification characteristics of five NSHSE indices in Fengjie County for the years 1997, 2005, and 2009. To be specific, mean values of the five indices were calculated at the township level using the five indices dataset obtained above and the township boundary layer derived from the administrative division map. The manual classification method was then applied to extract the spatial-temporal characteristics of five indices among the 30 townships. It is worth pointing out that, in order to directly explore the NSHSE and to reduce the influence of data from different years, the Jenks natural breaks classification method was used to divide the NSHSE into five levels (unsuitable: $<$ 47.22, critical-suitable: 47.23–51.88, low-suitable: 51.89–55.53, moderate-suitable: 55.54–59.42, and high-suitable: $>$ 59.42) according to the ranges of NSHSE values of Fengjie County in the years of 1997, 2005, and 2009.

In addition, global and local autocorrelations analyses (Anselin, 1995; Mitchell, 2005; Zhang et al., 2008) were also applied to further statistically analyze the spatial-temporal patterns of the NSHSE indices. Global Moran's I measures spatial autocorrelation, and it evaluates whether the pattern expressed is clustered, dispersed, or random based on calculating the Moran's I Index value (ranging from –1.0 – + 1.0) and both a *Z*-score and *p*-value. The *Z*-score (standard deviation) and *p*-value (probability) can determine if the interpretation is statistically significant. Furthermore, from a local perspective of autocorrelation, the Anselin Local Moran's I (Local Indicators of Spatial Association, LISA) (Anselin, 1995) identifies spatial outliers and spatial clusters of features with high or low values. It calculates a local Moran's I values, *Z*-scores, *p*-values, and codes (High-High Cluster, Low-Low Cluster, High-Low Outlier, and Low-High Outlier) representing the cluster type for each statistically significant feature. The *Z*-scores and *p*-values represent the statistical significance of the computed index values. High-High Cluster refers to a cluster of similar high values, and Low-Low Cluster means a cluster of similar low index values. High-Low Outlier represents a high index value outlier surrounded by lower index values, while Low-High Outlier is an outlier surrounded by high index values. Two types of spatial weight matrices, the conceptualization of inverse distance and continuity edges and corners, were adopted as the quantification of spatial relationships that describe how the polygon features interact with each other.

4 Results and discussion

4.1 Spatial-temporal quantification of NSHSE

Figures 4 and 5 show the spatial distribution and classification maps of NSHSE indices in 1997, 2005, and 2009. These figures show that natural suitability trends were first downward then upward, as RAI has remained unchanged while the rising HTC and WRI are considerably lower than that of the decline of LCI in 2005, but the rising LCI and WRI are higher than the decline of HTC in 2009. That is to say, this can be primarily explained by the construction of the Three Gorges Dam Project (TGDP). The Three Gorges Reservoir (TGR) began to store water in 2003, at which point the water level reached 135 m; in 2006, it reached 156 m, then 172 m in 2008, and 175 m (target level) in every year from 2010 until now (Wen et al., 2017). From above we can see that the rising of WRI in 2005 and 2009 is primarily owing to the water level rises periodically since 2003. Besides, the periodic change in water level may change the local climate in the surrounding reservoir areas (generally < 20 km) such as by increasing average temperature (Jiao, 2014).

Furthermore, throughout any one year, the TGR has a high water level in winter and spring and a low water level in summer and autumn. This periodic change in water level can potentially influence the vegetation variation in two ways. First, in winter, vegetation in the water level fluctuation zone (WLFZ, from 145 to 175 m) dies due to flooding; when the water level is reduced in summer, the WLFZ is exposed and vegetation grows but with distinct species diversity compared to the year prior. For example, the WLFZ were mainly covered by agricultural vegetation, shrubbery, and forests before the first impoundment of the TGR in 2003, while since 2003 the main vegetation types have been annual herbs (Wang et al., 2014). Second, the periodic change in water level of the TGR may affect vegetation activities in the surrounding areas as a result of changing the local climate in the surrounding reservoir areas which aforementioned.

It should be emphasized that anthropogenic activities are generally considered to have a large impact on vegetation variations and a close relationship with observed climate variations (Zhou et al., 2015). In other words, the early stage of the construction of the TGDP may have brought the risk of environmental degradation (e.g., soil erosion, non-point source pollution). In order to minimize the risk of environmental degradation and to protect the ecological security in the TGRA, a series of ecological projects, for example, the Soil and Water Conservation, Natural Forest Protection Project, Grain for Green Project, and Greenbelt, have been conducted by the national and local governments (TGPEEMSIMC, 2009) over the last decades. As a result, most crop-land distributed on steep slopes with gradients of 25° or more have been returned to forest or grassland. These projects have had a considerable, quite positive effect on vegetation sustainability which has increased NDVI (Fu et al., 2010; Han et al., 2013) as directly evidenced by the results presented in our study.

Generally, the NSHSE status of Fengjie County has an uneven distribution across the townships, especially between the southern and central areas. The majority of townships in the northwest and central (e.g., Yong'an, Yongle, Hongtu, and Qinglian) have higher NSHSE compared to those in the core area of the south side (e.g., Taihe, Chang'an Tujiazu, Longqiao, and Yunwu Tujiazu). In addition, the lowest value of NSHSE is found in the southern area, where high altitude mountains lie, because the townships in the southern part of the study area have evident disadvantages in RAI and HTC.

Based on the spatial characteristics of the NSHSE index, the natural breaks classification method was adopted to divide the NSHSE into five levels, including unsuitable, critical suitable, low suitable, moderate suitable, and high suitable areas (Fig. 6 and Table 4). The results show that:

1) In 1997, 2005, and 2009, the unsuitable regions comprised 151.73 km^2, 264.95 km^2, and 162.85 km^2, respectively, accounting for 3.71%, 6.48%, and 3.98% of the total area of this county. The unsuitable area is mainly found above the 1800 m elevation in the Qiyao and Wushan Mountains in the southern of Fengjie County.

2) Critical suitable districts cover areas of 758.31 km^2, 805.27 km^2, and 568.87 km^2, respectively, accounting for 18.55%, 19.70%, and 13.92% of the total area of this county. They are mainly located in the northeast, southwest, and southeast areas with higher elevations and steeper terrains, and they are scattered in the northwest and central areas of the study area, which corresponds to lower RAI, HTC, LCI, and WRI.

3) Low suitable districts cover areas of 1725.60 km^2, 1333.23 km^2, and 1059.84 km^2, respectively, accounting for 42.23%, 32.62%, and 25.93% of the total area of this county. They are mainly distributed in the valley region, the parallel ridge-valley region, and the low mountains and hills region; the distribution is dispersed, and the situation of these regions is different.

4) Moderate and high suitable districts cover areas of 1451.37 km^2, 1683.55 km^2, and 2295.44 km^2, respectively, accounting for 35.51%, 41.20%, and 56.17% of the total area of this county. They are mainly distributed in and near the Yangtze River, the Daxi River, and the Meixi River etc.; they are scattered in the flat regions between parallel ridge-valleys and parts of the transition zone, where the

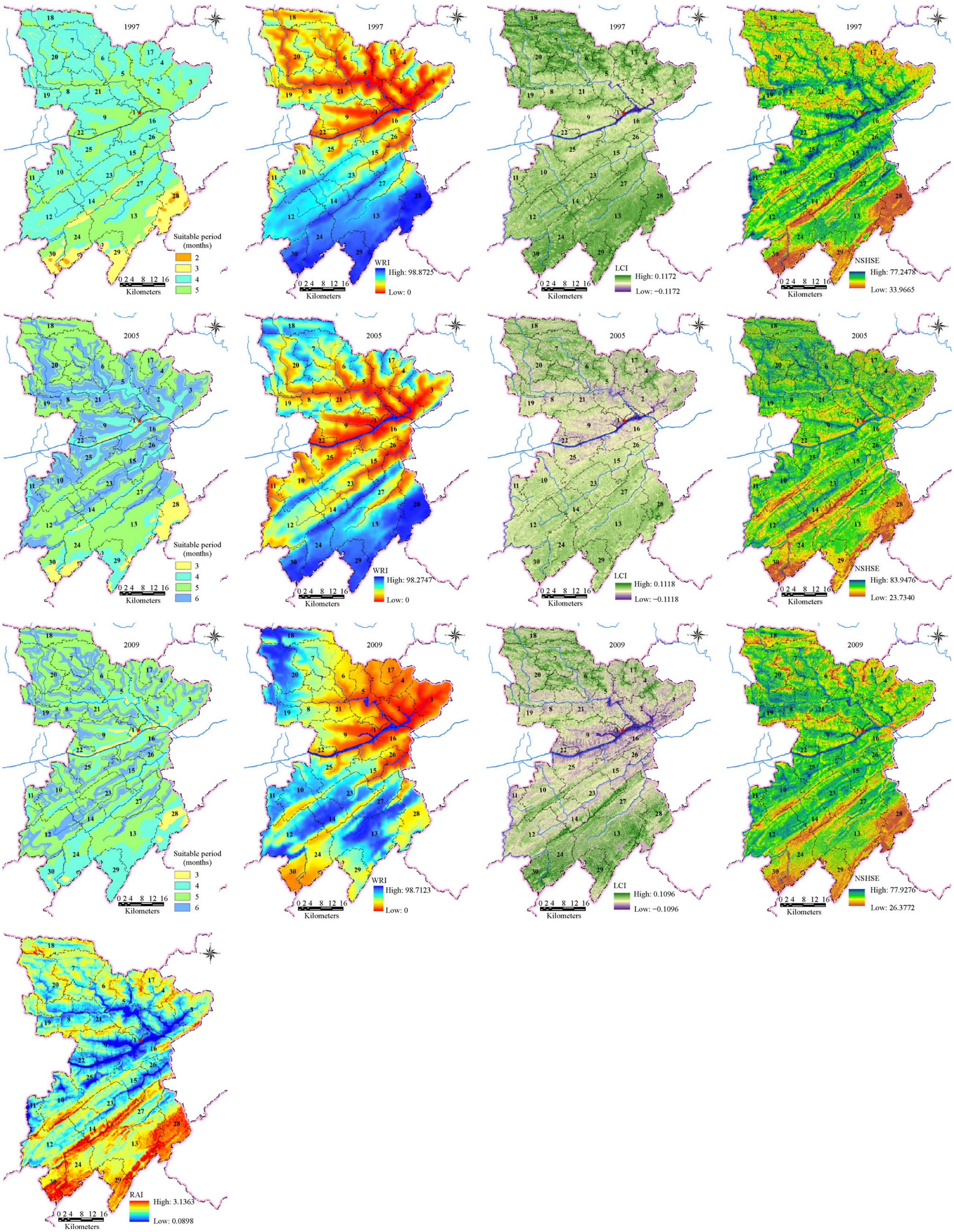

Fig. 4 Spatial distribution of NSHSE indices of Fengjie County in 1997, 2005, and 2009.

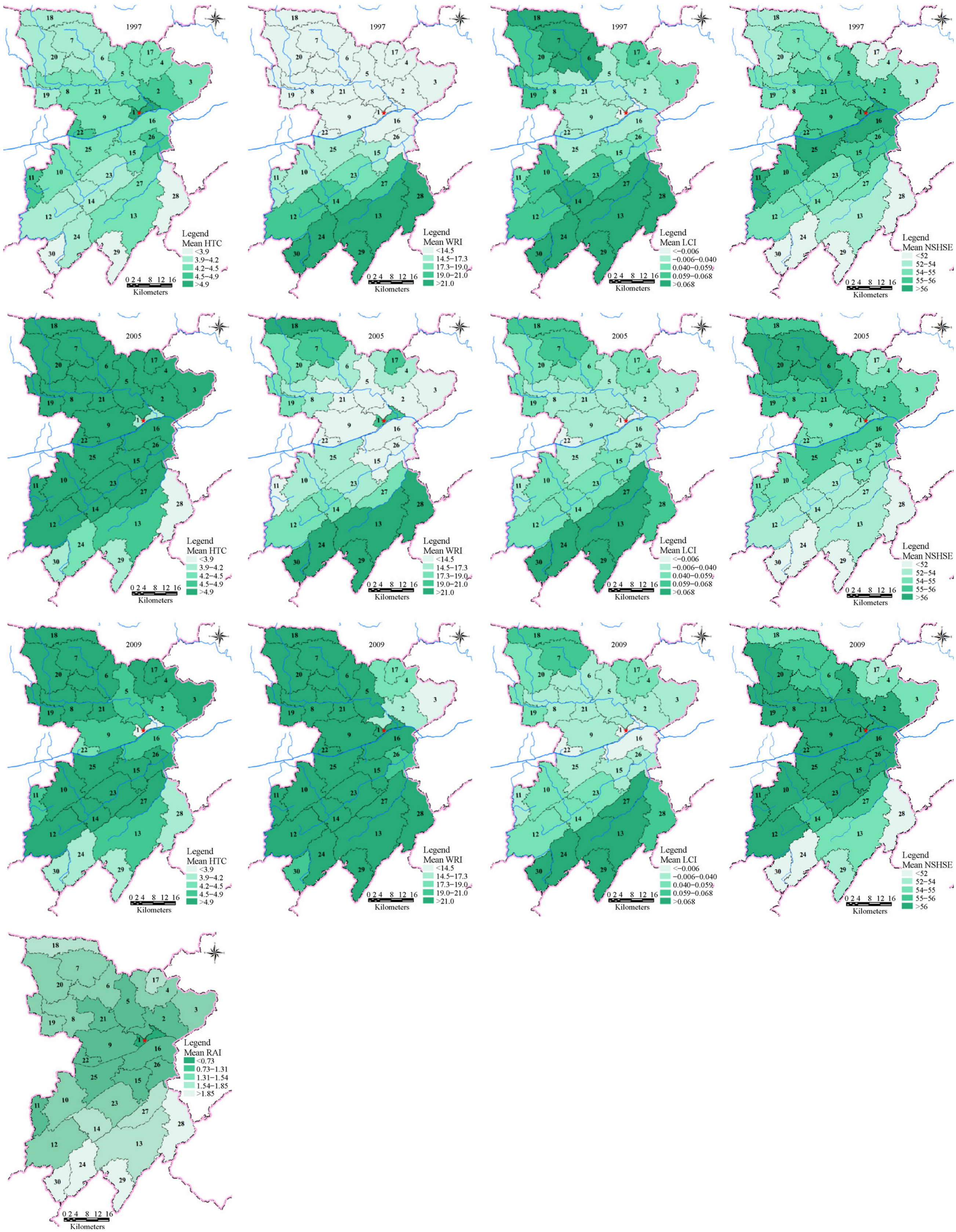

Fig. 5 Classification maps of NSHSE indices of Fengjie County in 1997, 2005, and 2009.

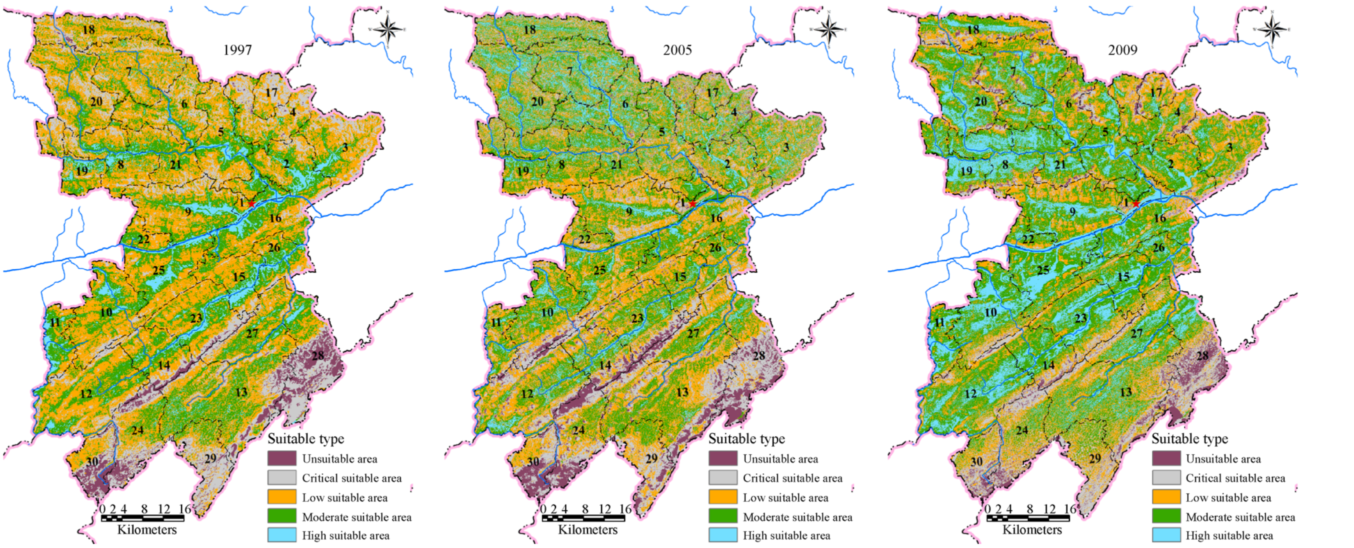

Fig. 6 Classification maps of NSHSE of Fengjie County in 1997, 2005, and 2009.

Table 4 Statistical areas of five suitable types of NSHSE of Fengjie County in 1997, 2005, and 2009

Suitable type	1997		2005		2009	
	Area/km^2	Percent/%	Area/km^2	Percent/%	Area/km^2	Percent/%
Unsuitable area	151.73	3.71	264.95	6.48	162.85	3.98
Critical suitable area	758.30	18.55	805.27	19.70	568.87	13.92
Low suitable area	1725.60	42.23	1333.23	32.62	1059.84	25.93
Moderate suitable area	1157.72	28.33	1232.51	30.16	1500.86	36.72
High suitable area	293.65	7.18	451.04	11.04	794.58	19.45

RAI is the best and the HTC, LCI, and WRI are better. The NSHSE is best in the regions where the density of the nearby river is high.

4.2 Spatial-temporal pattern analysis of NSHSE

The results of the spatial analysis demonstrate the spatial patterns of NSHSE in Fengjie County in 1997, 2005, and 2009. The Moran's I values returned by both spatial conceptualizations demonstrated positive spatial autocorrelations for most of the five NSHSE indices except for the HTC index in 1997, suggesting that their spatial patterns were statistically clustered across the townships. Both the p values and Z-scores retrieved from those five indices prove the identified patterns as significant at a confidence level of 99% (Table 5).

Figures 7 and 8 reveal a cluster of townships with a low NSHSE Index in the core area of the south side, and a cluster of neighborhoods with high NSHSE Index in the northwest and central corner of Fengjie County. This matches well with the conclusions mentioned in Section 4.1. Those clustered townships (e.g., Yunwu Tujiazu) with high altitude mountains have a low NSHSE Index. The mapped NSHSE indices indicate that the disparity between the two different clusters particularly exists in climate, topography, and water resources. In respect to the outliers, the continuity edges and corners conceptualization recognizes 1997 Xinglong as a High-Low outlier feature as it is a highly HTC township surrounded by lower HTC townships, while 1997 Chang'an Tujiazu is recognized as a Low-High outlier feature as it is a lowly HTC township surrounded by higher HTC townships. Both the inverse distance and continuity edges and corners conceptualizations recognize 2009 Yong'an as a High-Low outlier feature as it is a highly WRI township surrounded by lower WRI townships. This may be primarily attributed to the fact that the Yangtze River goes through the whole township, and it has been rich in water since the Three Gorges Dam was established.

4.3 Rationality analysis of population distribution

In order to illustrate the influence of NSHSE on population distribution and to provide better decision support for the resettlement of the Three Gorges Project, the rationality of population distribution of Fengjie County in 2009 was

Table 5 Global spatial pattern analysis based on two spatial conceptualizations

Indices	Conceptualization of spatial relationships	Moran's I index	*Z*-score (significant at the 0.10 level)	*p*-value	Global spatial pattern
RAI	Inverse distance	0.63	4.08	0.00	Clustered
RAI	Continuity edges and corners	0.57	4.72	0.00	Clustered
HTC1997	Inverse distance	0.22	1.63	0.10	Random
HTC1997	Continuity edges and corners	0.10	1.11	0.27	Random
HTC2005	Inverse distance	0.25	1.77	0.08	Clustered
HTC2005	Continuity edges and corners	0.25	2.29	0.02	Clustered
HTC2009	Inverse distance	0.23	1.64	0.10	Random
HTC2009	Continuity edges and corners	0.26	2.33	0.02	Clustered
WRI1997	Inverse distance	0.79	5.01	0.00	Clustered
WRI1997	Continuity edges and corners	0.77	6.23	0.00	Clustered
WRI2005	Inverse distance	0.48	3.13	0.00	Clustered
WRI2005	Continuity edges and corners	0.45	3.74	0.00	Clustered
WRI2009	Inverse distance	0.28	2.00	0.05	Clustered
WRI2009	Continuity edges and corners	0.34	3.00	0.00	Clustered
LCI1997	Inverse distance	0.61	4.09	0.00	Clustered
LCI1997	Continuity edges and corners	0.56	4.86	0.00	Clustered
LCI2005	Inverse distance	0.67	4.32	0.00	Clustered
LCI2005	Continuity edges and corners	0.58	4.78	0.00	Clustered
LCI2009	Inverse distance	0.72	4.58	0.00	Clustered
LCI2009	Continuity edges and corners	0.61	5.05	0.00	Clustered
NSHSE1997	Inverse distance	0.41	2.78	0.01	Clustered
NSHSE1997	Continuity edges and corners	0.32	2.83	0.00	Clustered
NSHSE2005	Inverse distance	0.57	3.84	0.00	Clustered
NSHSE2005	Continuity edges and corners	0.56	4.78	0.00	Clustered
NSHSE2009	Inverse distance	0.38	2.54	0.01	Clustered
NSHSE2009	Continuity edges and corners	0.37	3.22	0.00	Clustered

analyzed (Figs. 9 and 10). In general, the number of people living in the unsuitable and critical-suitable regions is about 0.095 million, which accounts for 8.92% of the total population. The number of people living in the moderate and high suitable regions is 0.760 million, accounting for 71.49% of the total population, which suggests that the distribution of the population is reasonable and that most people are living in a comfortable environment. Meanwhile, people living in unsuitable and critical-suitable regions should be first resettled in the resettlement of the Three Gorges Project. More specifically, villages and towns, such as Xinglong, Yanwan, Taihe, Longqiao, and Yunwu Tujiazu, should be considered for resettlement; in these regions, the proportion of people living in the moderate and high suitable region is less than 50% of the total population, which is especially true for villages and towns like Taihe, Longqiao, and Yunwu Tujiazu where the proportion of people living in the moderate and high suitable regions are 37.67%, 35.43%, and 20.93%, respectively. For Yong'an, Baidi, Caotang, Fenhe, Ping'an, Zhuyuan, and Chang'an Tujiazu, the number of people living in the moderate and high suitable region is below the average level (71.49%). The population distribution condition is reasonable for the remaining 18 villages and towns such as Gongping and Hongtu.

5 Conclusions

This study demonstrates how to spatial-temporally explore NSHSE based on a synthetic model and geostatistical pattern analysis. Sixteen NSHSE indices were calculated by using multi-source data for Fengjie County in 1997, 2005, and 2009. The spatial classification maps show that the trend of its natural suitability has shifted southward then northward, and there was evident disparity in its NSHSE status, especially with respect to RAI and HTC across the 30 townships for Fengjie in all three dates. A gap existed in the north and south sides of the county, which was particularly higher in the central areas and lower in the

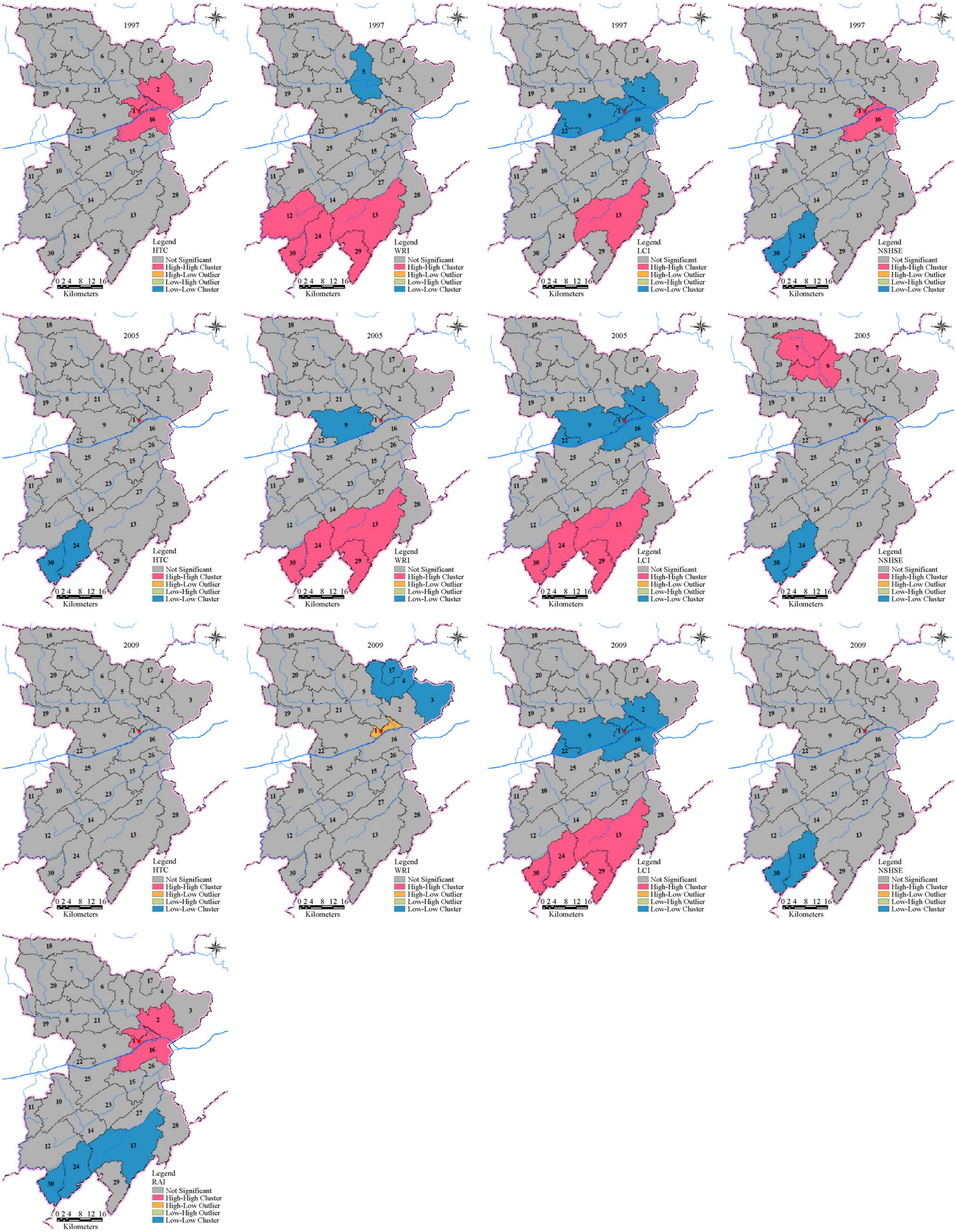

Fig. 7 LISA spatial analyses of NSHSE indices with inverse distance as the conceptualization of spatial relationships for Fengjie County in 1997, 2005, and 2009.

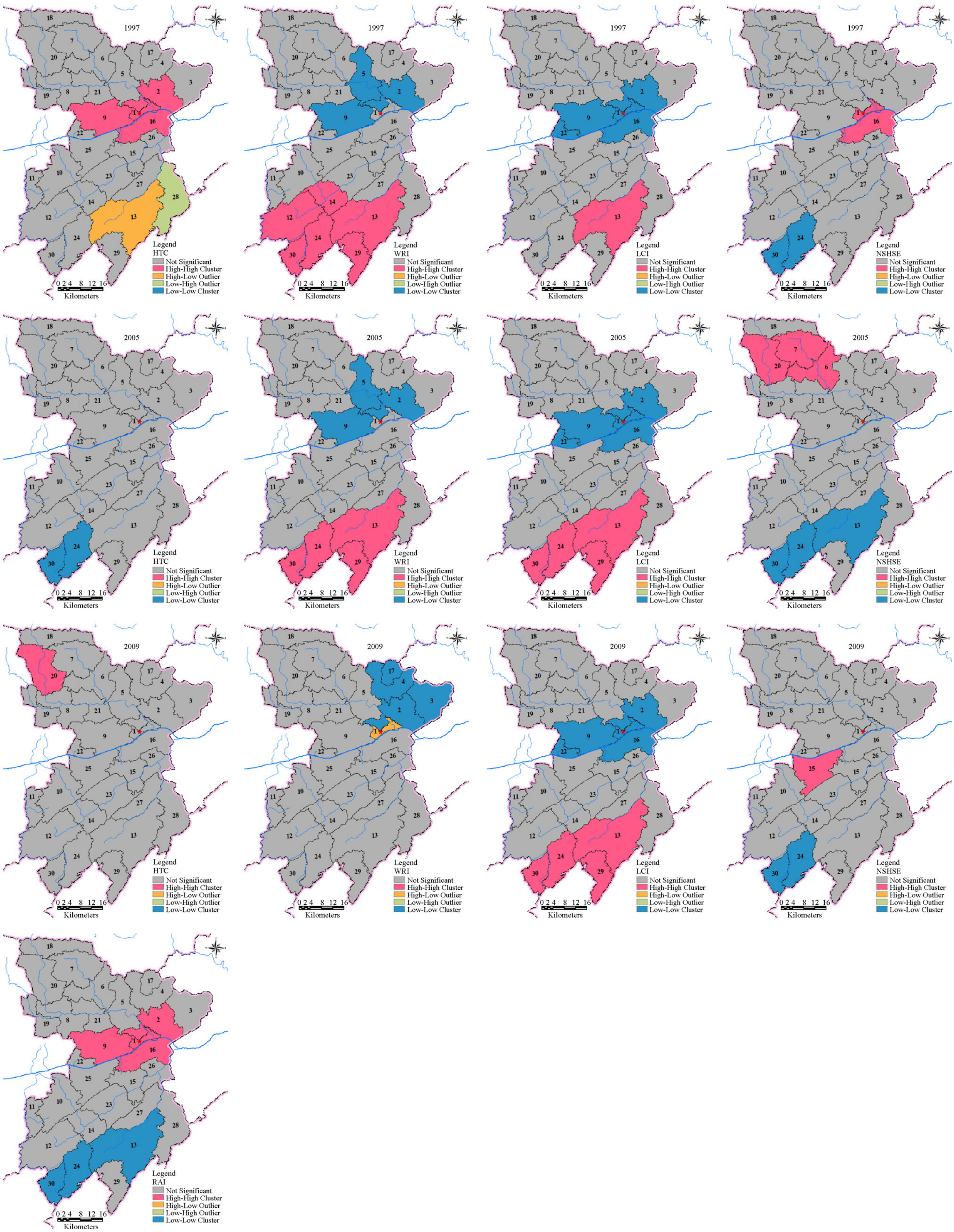

Fig. 8 LISA spatial analyses of NSHSE indices with continuity edges and corners as the conceptualization of spatial relationships for Fengjie County in 1997, 2005, and 2009.

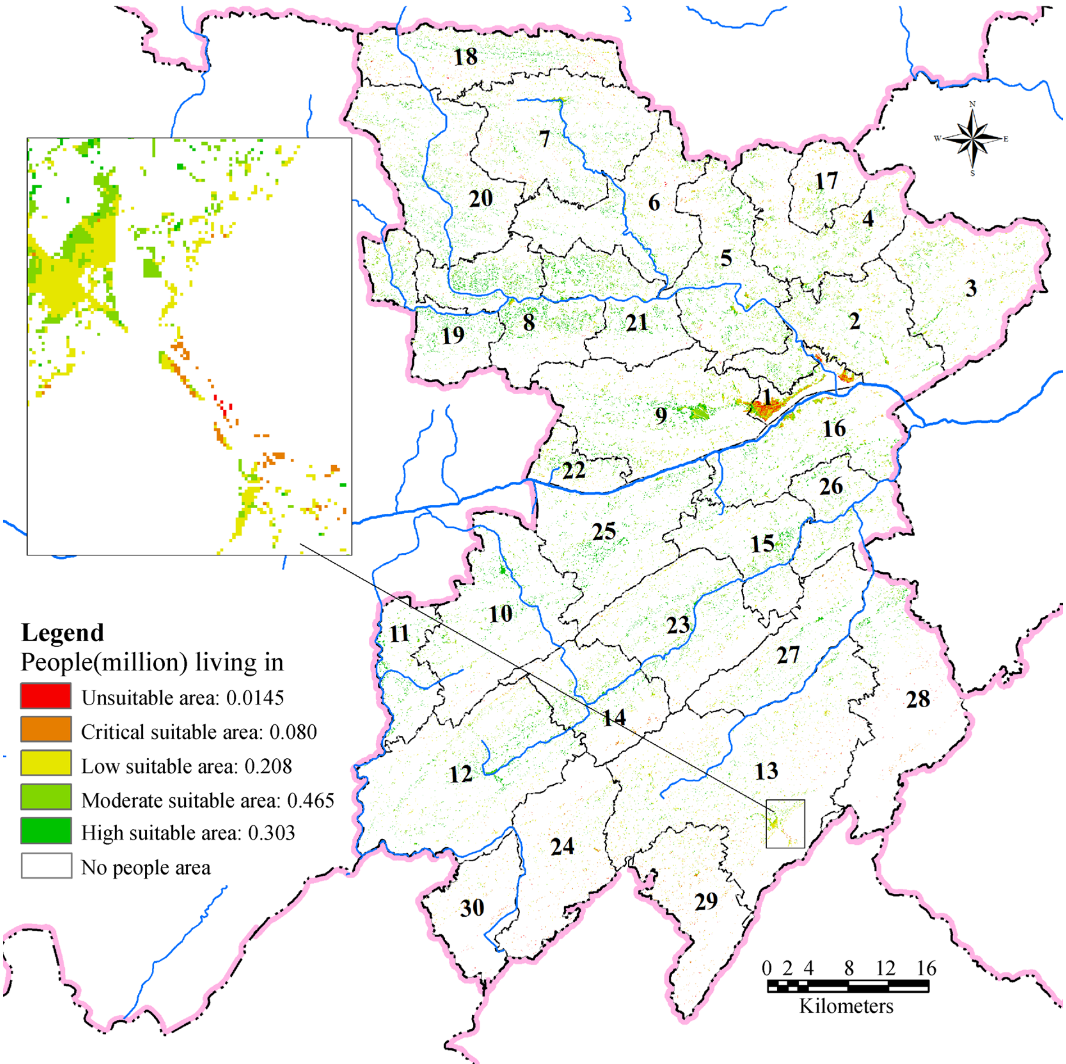

Fig. 9 Population distribution map of Fengjie County in 2009.

south of the inner county. The spatial statistical analysis further quantitatively described the spatial patterns of autocorrelations from global and local perspectives, and the analysis found that most of the five NSHSE indices (Relief Amplitude Index, Human Thermal Comfort, Water Resource Index, Land Cover Index, and Natural Suitability of Human Settlement Environment Index) showed statistically clustered patterns in the inner-county townships. In addition, in 1997, Xinglong was identified as an outlier township with a high HTC status but lower HTC townships surrounded it, while Chang'an Tujiazu was detected as a township with a low HTC but townships with higher HTC surrounded it. Also, in 2009, Yong'an was identified as a township in high WRI status but lower WRI townships surrounded it. The correlation coefficient between NSHSE and population density indicates that NSHSE has significant influence on population distribution. At the same time, the analysis shows that most people were living in moderate and high-suitable districts with a comfortable living environment, and therefore the distribution of the population is mostly reasonable.

Results also offer several possible avenues for future research. For example, the TGDP impacts a wide and complex range of natural and social environments and involves many different regions connected to the TGRA. The upper, middle, and lower reaches of the Yangtze River Basin, its mainstreams and tributaries, and its natural and social environment are mutually connected, restrained, and influenced. It therefore remains necessary to integrate the natural, social, and economic aspects of the region into a complex human environment to draw fully scientific and systematic conclusions. In addition, multi-source data with finer spatial resolution and higher temporal resolution can potentially help establish a better NSHSE model to quantitatively evaluate its spatial-temporal dynamics and potentially establish a human settlement database with multiple time and spatial scales. This could better provide decision support for the region's future HSE sustainable

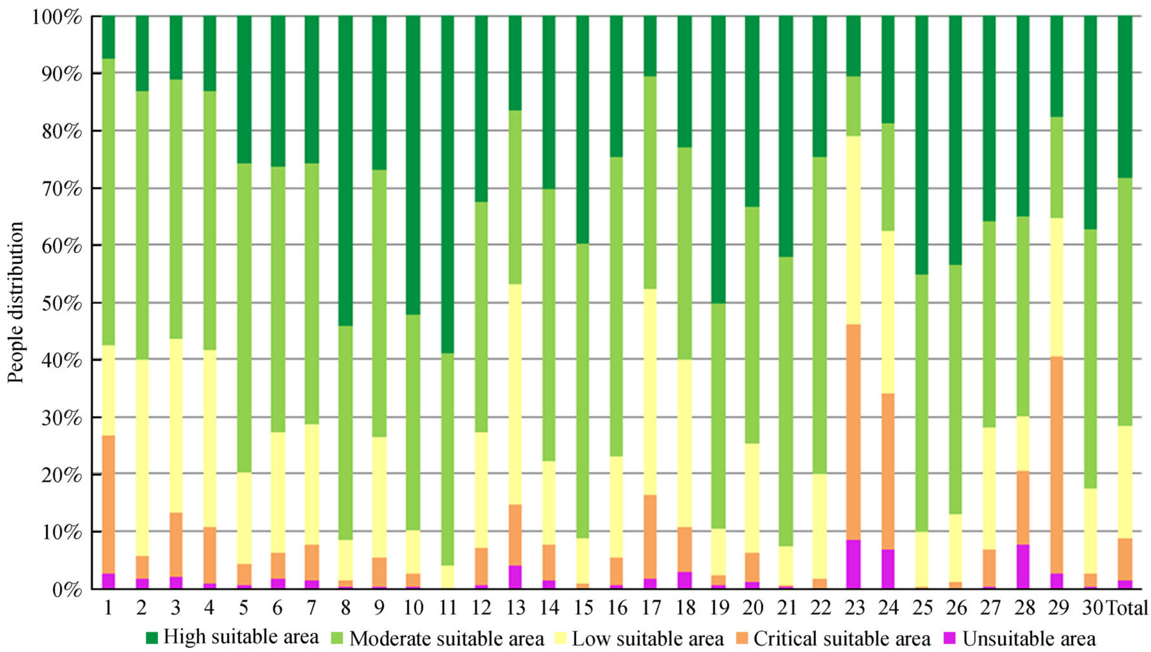

Fig. 10 Population distribution statistics of 30 townships in Fengjie County in 2009.

development strategy and guiding the population redistribution.

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